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**Galvanic Coupling Between
D6AC Steel, 6061-T6 Aluminum,
Inconel 718, and Graphite-
Epoxy Composite Material:
Corrosion Occurrence
and Prevention**

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TABLE OF CONTENTS

	Page
INTRODUCTION.....	1
PREVIOUS WORK.....	1
PART I. THE EFFECT OF GALVANIC COUPLING WITH G/E ON THE CORROSION RATES IN 3.5% NaCl SOLUTIONS OF BARE D6AC STEEL, INCONEL 718 AND 6061-T6 ALUMINUM	2
Experimental.....	2
Results and Discussion	3
Conclusions.....	3
PART II. THE PREVENTION OF GALVANIC CORROSION WHEN 6061-T6 ALUMINUM AND D6AC STEEL ARE COUPLED TO G/E	4
Experimental.....	4
Results and Discussion	5
A. Visual Examination of Specimens.....	5
B. Examination After Paint Removal.....	5
Conclusions.....	5
REFERENCES	15

LIST OF TABLES

Table	Title	Page
1.	Corrosion Potentials (SCE) of G/E, Inconel 718, D6AC Steel and 6061-T6 Al in 3.5% NaCl	6
2.	Galvanic Currents of Various Couples in 3.5% NaCl	6
3.	Corrosion Rates by Weight-Loss Methods for D6AC Steel, 6061-T6 Al and Inconel 718 in 3.5% NaCl.....	7
4.	Tests Performed for G/E-Metal Galvanic Corrosion.....	7
5.	Weight Losses from Corrosion for All Metal Samples	8

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Complete assembly for test No. 4 after removal from 3.5% NaCl solution	9
2.	Complete assembly for test No. 5 after removal from 3.5% NaCl solution	10
3.	Metal specimens for test No. 1 after exposure and cleaning.....	11
4.	Metal specimens for test No. 2 after exposure and cleaning.....	11
5.	Metal specimens for test No. 3 after exposure and cleaning.....	12
6.	Metal specimens for test No. 4 after exposure and cleaning.....	12
7.	Metal specimens for test No. 5 after exposure and cleaning.....	13
8.	Metal specimens for test No. 6 after exposure and cleaning.....	13

TECHNICAL PAPER

GALVANIC COUPLING BETWEEN D6AC STEEL, 6061-T6 ALUMINUM, INCONEL 718, AND GRAPHITE-EPOXY COMPOSITE MATERIAL: CORROSION OCCURRENCE AND PREVENTION

INTRODUCTION

This study was directed toward determining the galvanic coupling properties of Filament Wound Motor Case (FWC) materials proposed for the Solid Rocket Boosters of the Space Shuttle System. For the purpose of clarity, the study is divided into two parts. Part I discusses corrosion acceleration in 3.5% NaCl when bare D6AC steel, 6061-T6 aluminum and Inconel 718 are coupled to Graphite-Epoxy Composite Material (G/E) and are in electrical contact. Part II deals with corrosion preventative measures which might be used when such coupling occurs.

G/E is produced by heating polyacrylonitrile in air and then carbonizing it in an inert atmosphere at a much higher temperature. This process produces continuous filament bundles of graphite fiber which can be woven, twisted or chopped and then impregnated with selected epoxy resins to form sheets, tubes and even extruded structural members. The primary advantage of G/E for aerospace applications is its high strength to weight ratio [1].

Graphite behaves electrochemically like a noble metal, and suggests that the material will be cathodic to most metals upon galvanic coupling. Whether or not corrosion of the anode occurs is dependent on kinetic parameters, such as exchange current density of the cathodic reduction reaction, uncoupled corrosion rates, and area ratios as well as the potential difference between the cathodic and anodic members of the galvanic couple [2].

Mansfeld [3] pointed out that the magnitude of galvanic corrosion depends not only on the potential difference of dissimilar metals, but also on kinetic parameters such as corrosion rates of the uncoupled materials, Tafel slopes and area ratios. Essentially, three different conditions are possible. In the first, only a reduction reaction occurs at the cathode. If Tafel behavior is observed and charge transfer occurs in the reaction, then the measured galvanic current equals the dissolution current for the anode. In this situation weight-loss data should agree with galvanic current data. In the second situation, the anode remains in a region of mixed potentials so that a reduction as well as an oxidation reaction occurs on its surface while only a reduction takes place at the cathode. In situation 3, the reduction reaction at the cathode is under diffusion control. In this case, for equal areas of anode and cathode, the corrosion rate of the anode in a galvanic couple is equal to twice its uncoupled corrosion rate. In this study, the galvanic current density represents the increase in dissolution rate of the anode coupled to G/E and is therefore a valid quantity for use as a criterion for ranking alloys for galvanic compatibility with G/E.

PREVIOUS WORK

B. A. Miller and S. G. Lee [4] conducted a study of the corrosion rates of several selected aerospace alloys coupled to G/E in aerated neutral 3.5% NaCl solutions at 22°C. Galvanic current measurements were made and weight-loss tests were also conducted. Based on the arbitrary criterion of magnitude of galvanic current density, the acceptability by particular alloy is as follows:

Acceptable: Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo, Rene' 41, Inconel X, Inconel, AFC-77, PH 17-7, SS304, Be-Cu, SS301.

Borderline: Aluminum-Graphite Composite, MA87, SS-440C, Al 2024-T6, Al 2024-T3, 1020, Al 7075-T6, 4130.

Unacceptable: AF 1410, 300M, Al 2020-T651, and 4340 steel.

Fischer and DeLucia [5] conducted electrochemical tests to determine the nature of galvanic corrosion when G/E is coupled to aluminum, steel and titanium alloys in neutral 3.5% NaCl solution. Corrosion current density data showed that aluminum alloys, cadmium plated steel, and cadmium plated steel with chromate conversion coat are more reactive than Ti-6Al-4V when coupled to G/E.

Johnston and co-workers [6] also conducted electrochemical corrosion studies on G/E-alloy couples, and listed corrosion potentials for uncoupled G/E and various alloys versus the Saturated Calomel Electrode (SCE) in aerated 3.5% NaCl solution. Galvanic currents were also measured, and galvanic current densities versus pH for several G/E-metal couples in one molar, air saturated NaCl solutions were reported. It was concluded that G/E forms a significant galvanic couple with steel, aluminum and titanium.

Brown and Coomber [7] investigated the corrosion behavior of G/E-aluminum alloy galvanic couples in aqueous 5% NaCl solution, with corrosion potentials being reported for eight laboratory composites of G/E and one commercial composite. The steady state corrosion potential for the commercial composite was about +50 mv (SCE). For laboratory fabricated composites, the corrosion potentials were about +300 mv (SCE). Aluminum alloys were about 600 to 700 mv negative to SCE. It was concluded that there is a serious risk of galvanic corrosion at electrically conducting G/E-aluminum and G/E-cadmium plated mild steel joints, but no risk for G/E-stainless steel or G/E-Ti-6Al-4V couples.

D. G. Treadway [8] conducted a test program to develop and evaluate corrosion protection systems for use on G/E-Al and G/E-Ti joints. It was concluded that G/E-Al and G/E-Ti interface areas demand careful protection, but that conventional materials and techniques are adequate.

D. E. Prince [9] examined the corrosion characteristics of metal fasteners in intimate contact with G/E, and concluded that unprotected aluminum, cadmium plated steel and A286 corrosion resistant steel fasteners corrode much more rapidly in G/E than in aluminum. Ti-6Al-4V and multiphase (AMS 5758) fasteners showed no visible evidence of corrosion when in contact with G/E even after 500 hr of salt spray exposure.

PART I.

THE EFFECT OF GALVANIC COUPLING WITH G/E ON THE CORROSION RATES IN 3.5% NaCl SOLUTIONS OF BARE D6AC STEEL, INCONEL 718 AND 6061-T6 ALUMINUM

Experimental

The electrolyte used for galvanic testing was 3.5% NaCl at room temperature (22°C). For weight-loss tests the metal specimens, which were 3.8 cm square by 0.16 cm thick, were wet sanded with 400 grit silicon carbide paper, degreased in boiling trichloroethylene and bolted to a G/E sample which was 5.0 cm square and 2.5 cm thick. Since stainless steel has previously been found to be compatible with G/E [7], stainless steel bolts 0.48 cm in diameter were employed to provide electrical contact. The G/E and metal specimens were separated by 0.16 cm thick teflon washers having a surface area of 1 cm² to allow the NaCl solution

to penetrate the space between the G/E and metal specimens. After weighing the metal specimens, they were bolted to the G/E and immersed in a 3.5% NaCl solution for a period of one week, after which they were cleaned according to procedures described in ASTM G1-72 and re-weighed to determine weight loss.

For galvanic current measurements, metal samples approximately 3.8 cm square by 0.16 cm thick were used. These were bolted individually to a G/E sample 3.8 cm² by 0.60 cm thick using a teflon bolt, with a spacer consisting of three teflon washers placed between the metal and G/E to provide a spacing of approximately 0.32 cm. The galvanic current measurements in 3.5% NaCl were then made with an EG&G-PARC Model 350A corrosion measurement console and their values were recorded after an immersion period of 24 hr.

The corrosion potentials (SCE) of 6061 Al, G/E, D6AC steel and Inconel 718 were also measured, with the potentials being recorded after equilibrium had been established (24 hr).

Results and Discussion

The corrosion potentials (SCE) of G/E, Inconel 718, D6AC steel and 6061-T6 Al are listed in Table 1, with the galvanic currents for various couples listed in Table 2. For the G/E-metal couples, it may be seen from these tables that the galvanic currents are in the same order that would be predicted from potential differences, the galvanic current being the greatest for the G/E-Al couple and least for the G/E-Inconel couple. Falling out of order is the galvanic current for the Al-D6AC steel couple. The reason for the high value of the observed current is not known, but probably indicates a difference in the kinetic processes involved.

The corrosion rates from weight loss methods of uncoupled D6AC steel, 6061 Al and Inconel 718 are listed in Table 3, and the rates for the same specimens coupled separately to G/E and electrically grounded are also shown in the same table. Also shown is a case in which 6061-T6 Al, D6AC steel and G/E were connected together with electrical contact in order to determine the effectiveness of aluminum in acting as a sacrificial anode to prevent galvanic corrosion of D6AC steel.

As seen from Table 3, the corrosion rate for individually coupled 6061-T6 Al is 9.2 mils/yr (mpy), much greater than its uncoupled corrosion rate (1.1 mpy), while the corrosion rate for D6AC steel individually coupled to G/E is 6.3 mpy, also much greater than its uncoupled corrosion rate (2.6 mpy). For Inconel 718, the corrosion rate of the coupled specimen (0.03 mpy) is the same as that for the uncoupled specimen (0.03 mpy), and is very low when compared to those for D6AC steel and 6061-T6 Al.

Conclusions

The results of this study indicate that severe galvanic corrosion occurs when bare 6061-T6 Al and D6AC steel are coupled to G/E, while bare Inconel 718 is relatively unaffected and is compatible with G/E. The results also indicate, as shown in Table 3, that 6061-T6 Al is effective as a sacrificial anode, providing cathodic protection to D6AC steel when both are galvanically coupled to G/E.

PART II

THE PREVENTION OF GALVANIC CORROSION WHEN 6061-T6 ALUMINUM AND D6AC STEEL ARE COUPLED TO G/E

Experimental

It was established in Part I that galvanic corrosion results when bare 6061-T6 Al and D6AC steel are coupled to G/E. This section describes the corrosion preventative measures investigated.

In order to establish a rather large ratio of surface areas (G/E-metal surface), G/E specimens having dimensions of 24 by 16.5 by 3 cm and metal samples having the dimensions 7.6 by 5 by 0.16 cm were used. This resulted in a cathode to anode ratio of 11 to 1. The G/E specimens were cut from a filament wound motor case supplied by the Hercules Corporation. Six separate tests were run, as listed in Table 4, with each test being run in duplicate. The G/E specimens were slightly curved, but flat surfaces on the G/E, where the G/E-metal contact took place, were obtained by sanding the G/E surfaces with a belt sander.

In preparation for painting, the sharp edges on the G/E were rounded by filing, and the surfaces abraded with sandpaper followed by solvent-wiping with acetone. G/E surfaces, where applicable, were then spray painted with two coats of Rust-Oleum No. 9392 white epoxy paint. For tests 3 and 4, areas 10 by 7.6 cm were left bare, to be coated with polyurethane resin. These areas were then coated with Solithane 113 Polyurethane Resin. For test number 2, only an area 10 by 7.6 cm was coated with polyurethane resin, with the remainder of the G/E surface being left bare. In tests 1 and 6, the surfaces of the G/E were completely painted with Rust-Oleum white epoxy paint with no other coating being applied to the G/E, while in test 5 the G/E surface was completely bare. The D6AC samples were sandblasted to white metal and solvent rinsed with acetone. All D6AC steel samples were then coated with 2 to 2.25 mils (0.050 to 0.057 mm) of Rust-Oleum zinc-rich primer, Zinc-Seal C-9334 green. In addition, a topcoat of approximately 2 mils (0.050 mm) of Rust-Oleum white epoxy paint was applied to samples for test number 4.

The aluminum samples used in test 6 were first wiped with acetone, hot alkaline cleaned and treated with Smut-Go chromate deoxidizer. They were then treated with Iridite 14-2 (conversion coat) and given one coat of Bostik (463-6-3) epoxy chromate primer after which a topcoat of Bostik epoxy 443-3-100 was applied. The total thickness of topcoat plus primer was 2 to 2.5 mils (0.050 to 0.064 mm).

Scribe marks in the form of an X were made on both sides of all painted metal surfaces, after which a coating of Conoco HD Calcium Grease No. 2 was applied for all tests. The metal samples were bolted to the G/E specimens using 4.8 mm diameter stainless steel bolts, with electrical contact of the metal and G/E being verified with a resistance meter. Pieces of "Viton" rubber 1.4 mm thick separated the aluminum samples from the G/E in test number 6 with electrical contact being made through the stainless steel bolts. Figures 1 and 2 show the assembled test specimens.

The metal samples were weighed before painting in order to make weight-loss measurements possible after the testing period. The test samples were completely immersed in a 3.5% NaCl solution for a period of four weeks, after which they were removed, washed, and examined both visually and by weight-loss methods for corrosion which had occurred during the immersion period.

Results and Discussion

A. Visual Examination of Specimens

Photographs of the complete assemblies after removal from the 3.5% NaCl solution are shown in Figures 1 and 2 for tests 4 and 5 respectively. For test number 1, both the G/E and D6AC steel plate were in good condition, with no visible sign of rusting on the metal and no rust streaks on the G/E. Specimens 3 and 4, for test number 2, showed heavy rusting at the center of the scribe marks, with other rust spots being evident on the D6AC steel plates. Heavy rust streaks appeared on the G/E surface. For test number 3, small rust spots were evident at one corner of the D6AC steel plates on both specimens 5 and 6, with small rust streaks being evident on the G/E surfaces. In test number 4, a photograph of which is shown in Figure 1, all surfaces appeared in good condition with no rusting evident on the steel plates, numbers 7 and 8. For test number 5, shown in Figure 2, heavy rusting was evident along one scribe mark for steel specimen 9 and in the center of the scribe marks for steel specimen number 10. Heavy rust streaks appeared on the G/E surfaces in both cases. For test number 6, which comprised the test for aluminum samples, all surfaces appeared in good condition, although a small amount of white Al_2O_3 formed in the scribe marks on the aluminum plates. This condition was difficult to determine visually.

B. Examination After Paint Removal

Paint was stripped from all metal samples after disassembly with Cee-Bee A-202 epoxy and polyurethane stripper, after which they were cleaned according to procedures described in ASTM G1-72 and weighed to determine weight loss. Photographs are shown in Figures 3 through 8 for the metal specimens in tests 1 through 6. Weight losses for each specimen are listed in Table 5, along with the average weight loss obtained in each test. For test number 1, the average weight loss was 32.1 mg, a rather small value, with the cleaned surfaces being in good condition. For test number 2, specimen number 3 exhibited a circular pit approximately 6 mm in diameter with corrosion all the way through the metal. The weight loss in this case was 246.7 mg. Specimen number 4 displayed a large oblong pit approximately 5 by 10 mm at the surface corroded to a depth of 1 mm. Weight loss for this case was 459.2 mg. The average weight loss for test number 2 was 353.0 mg. Specimens 5 and 6 for test number 3 had exhibited small rust spots at the corners, but the metal appeared in good condition after stripping and cleaning. This test showed an average weight loss of only 17.0 mg. For test number 4, where a topcoat had been applied over the zinc-rich primer, specimens 7 and 8 displayed an average weight loss of only 12.9 mg and appeared in very good condition. For test number 5, where the G/E surfaces had been left completely bare heavy corrosion occurred on both specimens. Specimen 9 displayed two large pits along one scribe mark. One of the pits was approximately 3 by 5 mm at the surface and had corroded to a depth of 1.5 mm. The other pit measured 5 by 7 mm at the surface and had corroded to a depth of 0.5 mm. Specimen number 10 exhibited a circular pit approximately 8 mm in diameter which had corroded all the way through the metal. Weight loss for these specimens averaged 389.4 mg. For test number 6, which involved the aluminum specimens and G/E completely covered with topcoat, the aluminum samples appeared in very good condition after cleaning, and exhibited an average weight loss of only 12.3 mg.

Conclusions

From the experimental results obtained, it is evident that the surfaces of the G/E must be completely coated, either with topcoat or a combination of polyurethane resin and topcoat. In test number 2, where only a polyurethane joint was employed with the remainder of the G/E surface left bare, heavy corrosion

occurred at the scribe marks in the metal surfaces, where only Conoco grease served to protect the bare metal. The remainder of the metal surfaces, which were coated with zinc-rich primer and Conoco grease, appeared to be in relatively good condition. The same situation was present in test number 5, where the total G/E surfaces were left bare.

The results also indicate that, when the G/E is completely coated, satisfactory protection of the D6AC steel is achieved with either the zinc-rich primer or the primer/topcoat combination, as shown by comparing tests 3 and 4, which had very similar weight losses. This is true despite the small rust spots observed at the corners of the metal plates in test number 3. These may have been caused by sharp corners on the metal plates.

For the case of aluminum in test number 6, the condition of the aluminum was very good and the weight loss was rather small. Although Conoco grease was used as a final coat for the aluminum plates, it is likely that equally good results would have been obtained without Conoco grease.

While these test show, in a general manner, effective methods for reducing the galvanic corrosion effects in salt water of G/E when coupled to D6AC steel and 6061 aluminum, it should be recognized that additional tests will be required before final recommendations can be made on specific treatments required for the FWC components. These should include test specimens which closely duplicate the proposed D6AC to G/E motor case joint as to materials and configuration, including relative size relationships between components, as well as expected environmental exposure conditions.

TABLE 1. CORROSION POTENTIALS (SCE) OF G/E, INCONEL 718, D6AC STEEL AND 6061-T6 AL IN 3.5% NaCl

Material	Potential(V)
G/E	+0.048
Inconel 718	-0.238
D6AC Steel	-0.692
6061-T6 Al	-0.770

TABLE 2. GALVANIC CURRENTS OF VARIOUS COUPLES IN 3.5% NaCl

Alloy	Coupled To	I_g (Micro A/cm ²)
D6AC Steel	G/E	12.06
6061-T6 Al	G/E	13.64
Inconel 718	G/E	1.31
6061-T6 Al	D6AC Steel	11.81

TABLE 3. CORROSION RATES BY WEIGHT-LOSS METHODS FOR D6AC STEEL,
6061-T6 Al AND INCONEL 718 IN 3.5% NaCl

Condition	D6AC Steel (mpy)	6061-T6 Al (mpy)	Inconel 718 (mpy)
A. Uncoupled	2.6	1.1	0.03
B. Individually Coupled to G/E With Electrical Contact	6.3	9.2	0.03
C. 6061-T6 Al, D6AC Steel and G/E Connected Together With Electrical Contact	2.4	9.5	

TABLE 4. TESTS PERFORMED FOR G/E – METAL GALVANIC CORROSION

1. D6AC Steel + Primer; G/E + Topcoat; Bare Joint; Conoco Grease on Metal (Specimen Nos. 1 and 2).
2. D6AC Steel + Primer; G/E (Bare); Polyurethane Joint; Conoco Grease on Metal (Specimen Nos. 3 and 4).
3. D6AC Steel + Primer; G/E + Topcoat; Polyurethane Joint; Conoco Grease on Metal (Specimen No. 5 and 6).
4. D6AC Steel + Primer + Topcoat; G/E + Topcoat; Polyurethane Joint; Conoco Grease on Metal (Specimen Nos. 7 and 8).
5. D6AC Steel + Primer; G/E (Bare); Bare Joint; Conoco Grease on Metal (Specimen Nos. 9 and 10).
6. 6061-T6 Aluminum + Paint; G/E + Topcoat; “Viton” Rubber Separation at Joint; Conoco Grease on Metal (Specimen Nos. 11 and 12).

TABLE 5. WEIGHT LOSSES FROM CORROSION FOR ALL METAL SAMPLES

Material	Test	Specimen	Weight-Loss (mg)	Average Weight-Loss (mg)
D6AC Steel	1	1	43.3	32.1
		2	20.9	
D6AC Steel	2	3	246.7	353.0
		4	459.2	
D6AC Steel	3	5	18.7	17.0
		6	15.3	
D6AC Steel	4	7	9.5	12.9
		8	16.2	
D6AC Steel	5	9	397.0	389.4
		10	381.7	
6061-T6 Al	6	11	13.2	12.3
		12	11.4	

NOTE: Results were obtained for 28 days exposure to 3.5% NaCl.

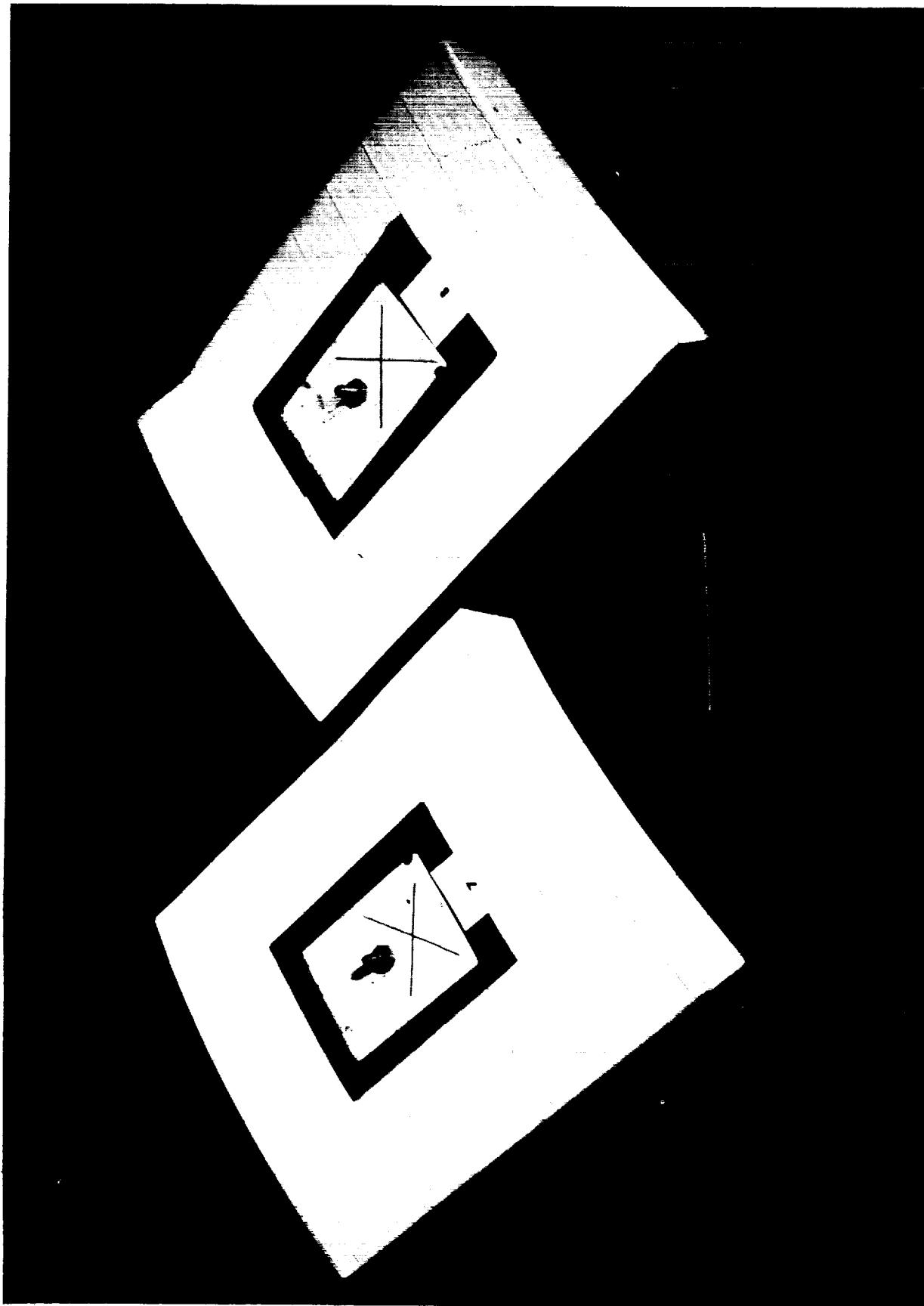


Figure 1. Complete assembly for test No. 4 after removal from 3.5% NaCl solution.

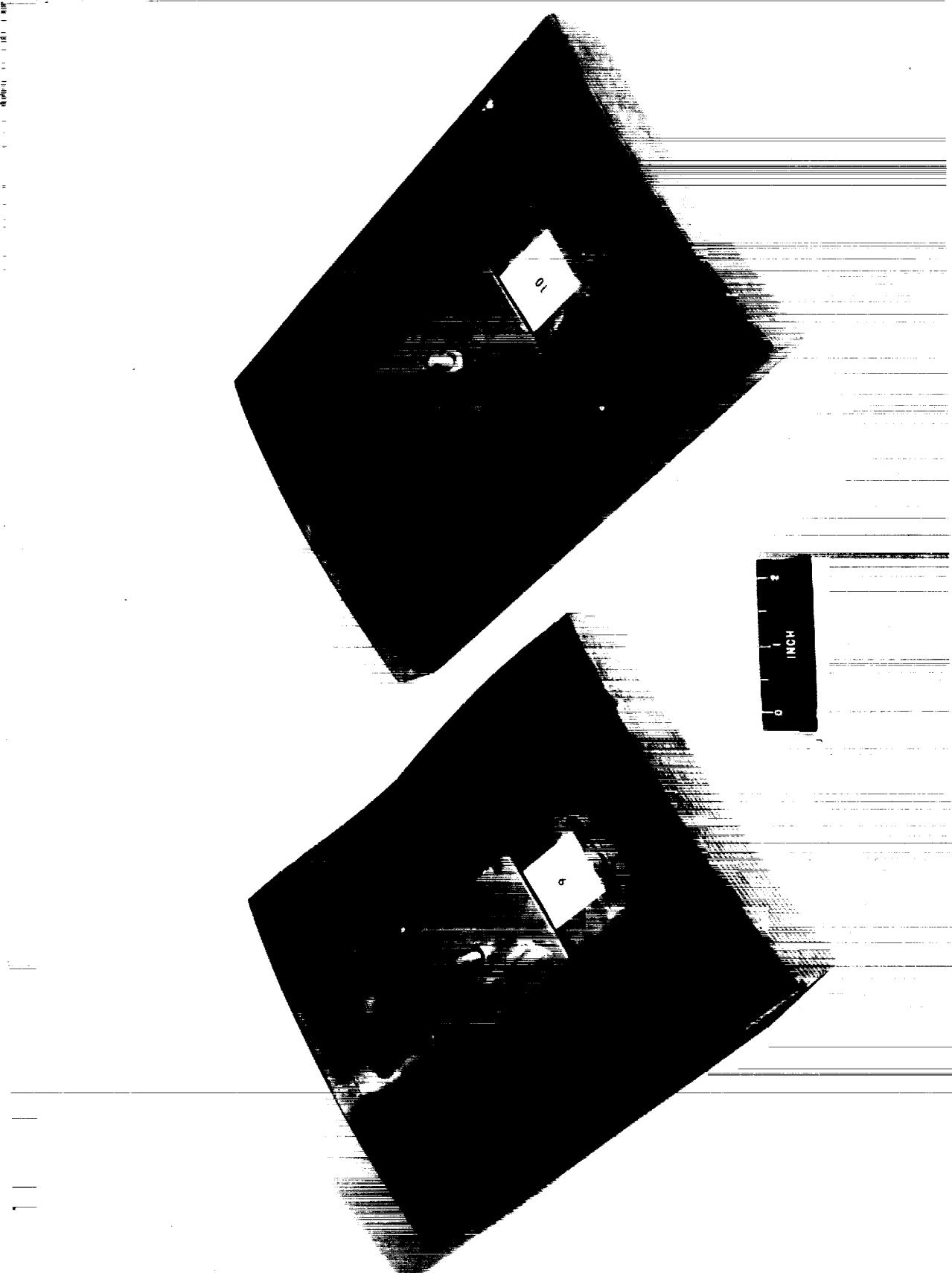


Figure 2. Complete assembly for test No. 5 after removal from 3.5% NaCl solution.

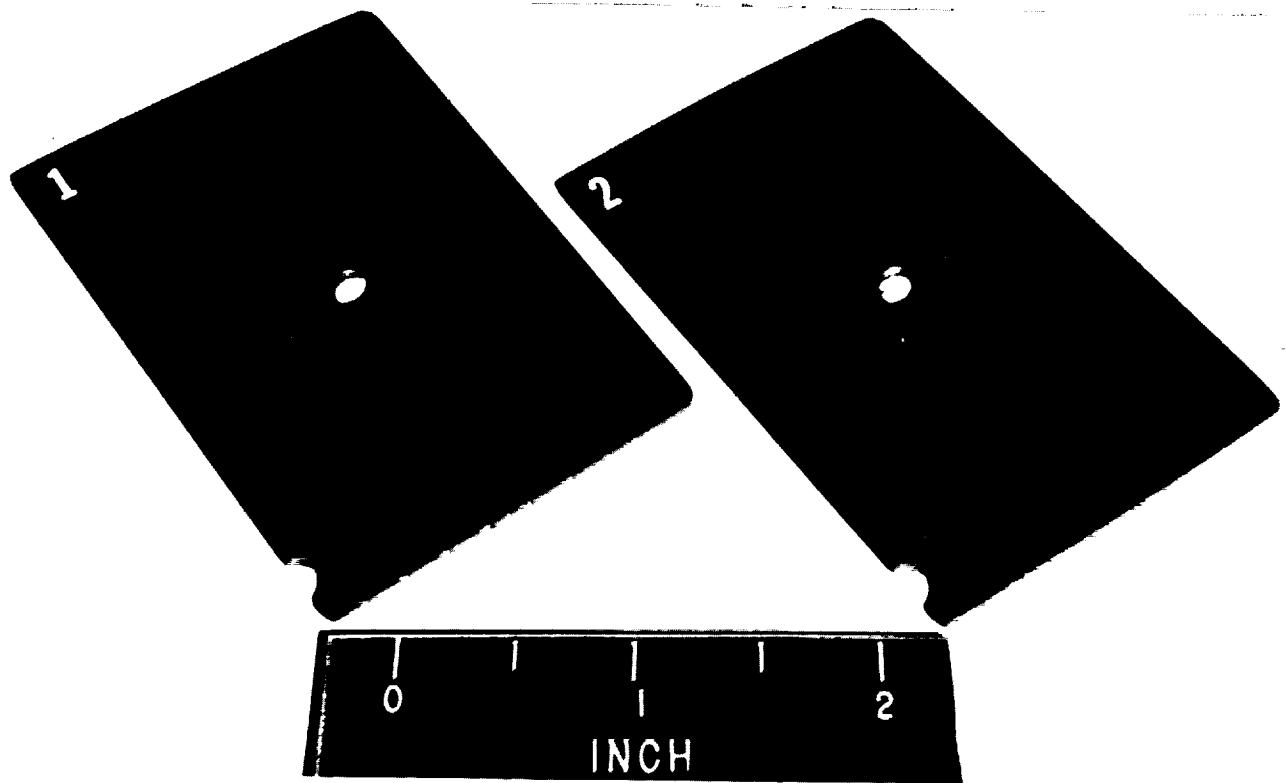


Figure 3. Metal specimens for test No. 1 after exposure and cleaning.

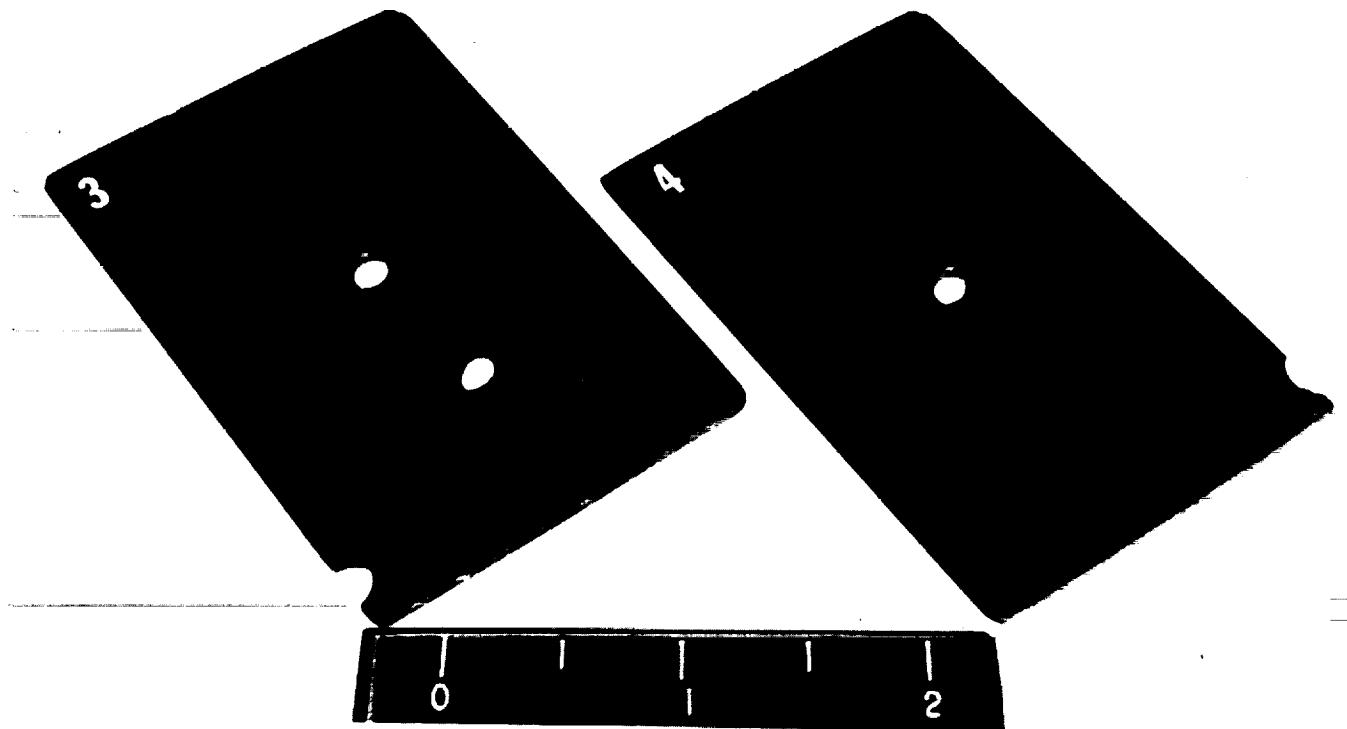


Figure 4. Metal specimens for test No. 2 after exposure and cleaning.



Figure 5. Metal specimens for test No. 3 after exposure and cleaning.

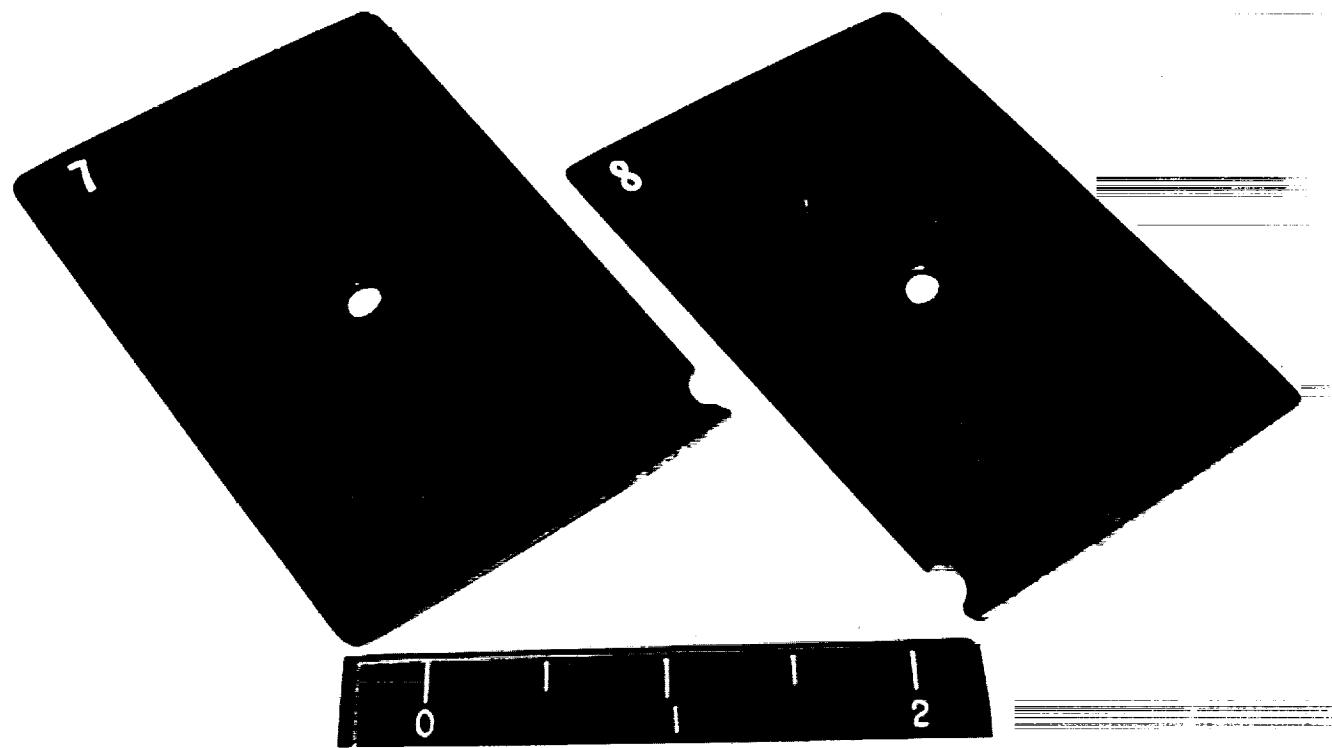


Figure 6. Metal specimens for test No. 4 after exposure and cleaning.

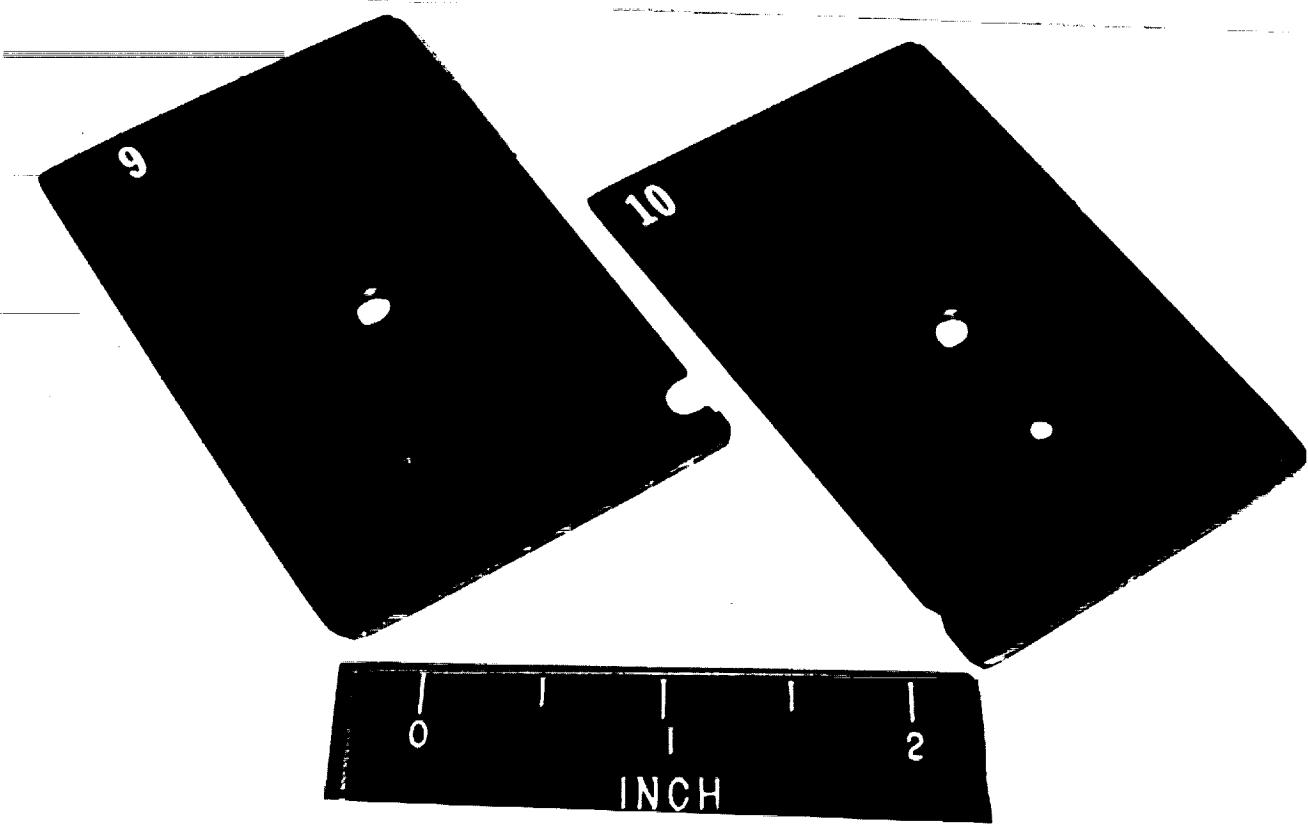


Figure 7. Metal specimens for test No. 5 after exposure and cleaning.

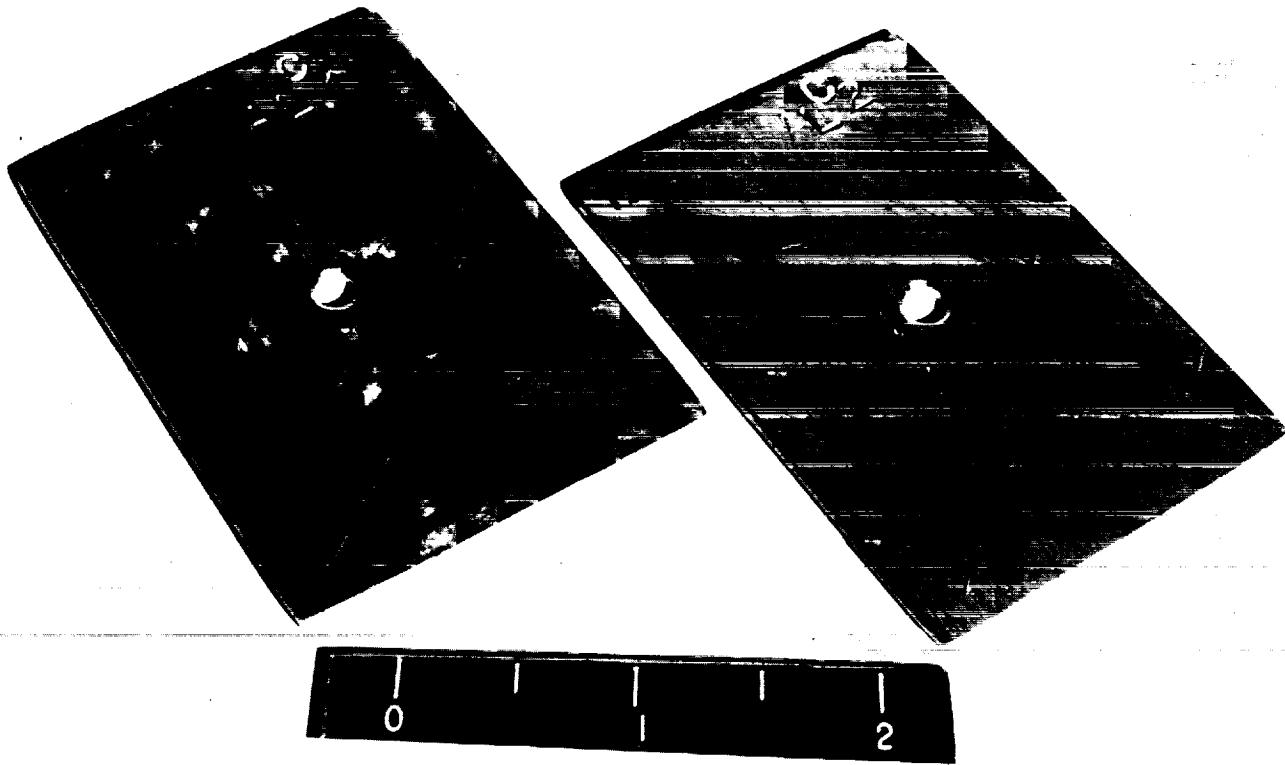


Figure 8. Metal specimens for test No. 6 after exposure and cleaning.

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16. ABSTRACT The effects of galvanic coupling between D6AC steel, 6061-T6 aluminum, Inconel 718*, and Graphite-Epoxy Composite Material (G/E) in 3.5% NaCl have been studied. Measurements of corrosion potentials, galvanic currents and corrosion rates of the bare metals using weight-loss methods have served to establish the need for corrosion protection in cases where D6AC steel and 6061-T6 aluminum are galvanically coupled to G/E in salt water while Inconel 718 was shown to be compatible with G/E. Six tests were made to study corrosion protective methods for eliminating galvanic corrosion in the cases of D6AC steel and 6061-T6 aluminum coupled to G/E. These results indicate that, when the G/E is completely coated with paint or a paint/polyurethane resin combination, satisfactory protection of the D6AC steel is achieved with either a coat of zinc-rich primer or a primer/topcoat combination. Likewise, satisfactory corrosion protection of the aluminum is achieved by coating it with an epoxy coating system.			
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